SYSTEMS AND METHODS FOR PLASMA CONTAINMENT

Priority Applications

[0001] This application claims priority benefit of United States Provisional Patent Application No. 60/456,832 filed March 21, 2003, titled "A Method of Obtaining Design Parameters for a Compact Thermonuclear Fusion Device," which is incorporated herein by reference in its entirety.

Background

Field

[0002] The present teachings generally relate to the field of plasma containment and more particularly, to systems and methods for establishing a stable plasma in a relatively compact containment chamber.

Description of the Related Art

[0003] Nuclear fusion occurs when two relatively low mass nuclei fuse to yield a larger mass nucleus and reaction products. Because a substantial amount of energy is associated with the reaction products, controlled nuclear fusion research is an ongoing process with efficient power generation being one of the important goals. For fusion to occur, two nuclei need to interact at a nuclear level after overcoming the mutually repulsive Coulomb barrier. Different methods can be used to promote such an interaction.

[0004] One widely-used method of promoting the fusion process is to provide a volume of plasma having the fusable ions at sufficient density and temperature. Such a plasma needs to be contained sufficiently long enough to allow the fusion reaction to occur. Preferably, such a containment substantially isolates the plasma from the surrounding environment to reduce heat loss.

[0005] One way to contain the fusionable plasma is to use magnetic fields to "pinch" and restrict the plasma to certain volumes. One magnetic confinement design commonly referred to as a "tokamak" restricts the plasma in a donut shaped (toroid) volume. Because many conventional magnetically confined fusion devices are geared toward power production, confinement volumes are designed to be large. Consequently, such large devices

and various supporting components can be prohibitively complex and/or expensive to operate in widespread applications.

Summary

[0006] The foregoing drawbacks associated with large fusion devices can be overcome by a containment method and apparatus that allows formation of a relatively small volume of fusionable plasma and by enhancing stability. Such a plasma can be designed by determining a stable energy state of the system without imposing a quasi-neutrality condition. A contained fusionable plasma having a relatively small dimension includes a substantial induced electrostatic field that contributes significantly to the stability of the plasma. Compact devices based on such contained plasmas can be used in different applications, such as a neutron generator, a x-ray generator, and a power generator.

[0007] One aspect of the present teachings relates to a two-mode plasma containment apparatus that includes a plasma disposed within a containment volume with a containment dimension. The plasma includes a number of electrons and a number of ions, and the electrons act as charge carriers in a current established in the plasma. The apparatus further includes a magnetic field that influences the electrons substantially more than the ions such that the electrons are magnetically confined as a first mode of confinement to an electron confinement volume that is smaller than the containment volume. Such a confinement causes at least a partial separation in distributions in the number of electrons and the number of ions. The separation induces an electrostatic field that facilitates confinement of the ions as a second mode of confinement within the containment volume.

[0008] Another aspect of the present teachings relates to a plasma chamber that includes a plasma having electrons and ions. The plasma chamber further includes a magnetic field having a shape and size that substantially confines the electrons within a restricted volume characterized by a volume scale length. The volume scale length has a size determined by an electron skin depth within the restricted volume. The electrons and the ions are maintained in overlapping spatial distributions within the restricted volume. The overlapping spatial distributions generates a substantial bulk electrostatic field within the restricted volume that stabilizes the overlapping spatial distributions and confines the ions substantially within the restricted volume.

[0009] Yet another aspect of the present teachings relates to a method for designing a plasma containment device. The method includes generating a characterization of the energy of a plasma system having a distribution of electrons and a distribution of ions. The characterization includes an energy term associated with a bulk electrostatic field induced inside the plasma by dissimilarities between the distribution of electrons and the distribution of ions. The method further includes determining an equilibrium state associated with the characterization of the energy of the plasma system. The method further includes determining one or more plasma parameters associated with the equilibrium state.

[0010] Yet another aspect of the present teachings relates to a plasma fusion device that includes a plasma reaction chamber having a plasma confined therein. The plasma includes a number of electrons and a number of ions. The plasma fusion device further includes a confinement field generator that provides a magnetic field to the reaction chamber thereby facilitating confinement of the plasma substantially within a plasma confinement volume. The plasma fusion device further includes a reaction fuel supply that provides one or more species of ions that can fuse under a plasma condition so as to yield a reaction product. The electrons act as charge carriers in a current established in the plasma thereby causing the magnetic field to influence the electrons more than the ions. Such a magnetic confinement causes at least a partial separation in distributions in the number of electrons and the number of ions. Such separation induces an electrostatic field that facilitates confinement of the ions within the plasma reaction chamber. The plasma confinement volume is characterized by a volume scale dimension. In one embodiment, the reaction product includes neutrons such that the fusion device is used as a neutron generator. In one embodiment, the reaction product includes energy such that the fusion device is used as a power generator.

[0011] Yet another aspect of the present teachings relates to an x-ray generator that includes a plasma chamber having a plasma confined therein. The plasma includes a number of electrons and a number of ions. the x-ray generator further includes a confinement field generator that provides a magnetic field to the plasma chamber thereby facilitating confinement of the plasma substantially within a plasma confinement volume. The electrons act as charge carriers in a current established in the plasma thereby causing the magnetic field to influence the electrons more than the ions. The magnetic confinement

causes at least a partial separation in distributions in the number of electrons and the number of ions. The separation induces an electrostatic field that facilitates confinement of the ions within the plasma chamber. The plasma confinement volume is characterized by a volume scale dimension. In one embodiment, such a confined plasma generates soft x-rays under conditions that include non-fusing plasma conditions.

[0012] Yet another aspect of the present teachings relates to a plasma containment apparatus that includes a plasma disposed within a containment volume having a containment dimension. The plasma includes a number of electrons and a number of ions, and the ions act as charge carriers in a current established in the plasma. The apparatus further includes a magnetic field that influences the ions substantially more than the electrons such that the ions are magnetically confined to an ion confinement volume that is smaller than the containment volume so as to cause at least a partial separation in distributions in the number of ions and the number of electrons. The separation induces an electrostatic field that facilitates confinement of the electrons within the containment volume.

[0013] Yet another aspect of the present teachings relates to a dimension associated with electron confinement volume, volume scale length, volume scale, ion confinement volume, and the like, of a confined plasma. In one embodiment, the dimension ranges between approximately 1 to approximately 1000 electron skin depths. In one embodiment, the dimension ranges between approximately 1 to approximately 100 electron skin depths. In one embodiment, the dimension ranges between approximately 1 to approximately 60 electron skin depths. In one embodiment, the dimension ranges between approximately 1 to approximately 40 electron skin depths. In one embodiment, the dimension ranges between approximately 1 to approximately 10 electron skin depths. In one embodiment, the dimension ranges between approximately 1 to approximately 2 electron skin depths. In one embodiment, the dimension is approximately 2 electron skin depths.

[0014] Yet another aspect of the present teachings relates to a stable plasma having electrons and ions, where magnetic confinement influences one species more than the other species. The amount of magnetic confinement influence can be characterized as a bulk motion or a flow of a species in the plasma. Such a confinement causes at least a partial separation in distributions of the electrons and ions. The separation induces an electrostatic field that facilitates confinement of the species that is the lesser affected by the magnetic

confinement. In one embodiment, electrons provide substantially all of the bulk motion. In one embodiment, ions provide substantially all of the bulk motion. In one embodiment, both electrons and ions provide bulk motions.

Brief Description of the Drawings

[0015] **Figure 1** shows a contained plasma having a bulk electrostatic field induced inside the plasma due to a difference in the spatial distributions of electrons and ions;

[0016] **Figure 2** shows a process for determining a steady-state equilibrium of the plasma having the induced E-field;

[0017] **Figure 3** shows one embodiment of a contained plasma having a cylindrical symmetry such that the electron and ion densities depend on radial distance r from the Z axis;

[0018] **Figure 4A** shows a Z-pinch containment of the cylindrically symmetric plasma of **Figure 3**;

[0019] **Figure 4B** shows a theta-pinch containment of the cylindrically symmetric plasma of **Figure 3**;

[0020] **Figure 5** shows how a high aspect ratio toroidal containment may be estimated by a cylindrical geometry;

[0021] **Figure 6** shows one embodiment of an azimuthal magnetic field profile that provides a Z-pinching;

[0022] **Figure 7** shows one embodiment of a stable confinement of electrons by a magnetic force that substantially offsets forces due to E-field and pressure;

[0023] **Figure 8** shows one embodiment of a stable confinement of ions by an electrostatic force that substantially offsets a force due to pressure;

[0024] **Figure 9A** shows one embodiment of a E-field profile that results from different spatial distributions of confined electrons and ions;

[0025] **Figure 9B** shows the electron and ion distributions of **Figure 9A** on a logarithmic scale;

[0026] **Figure 10** shows one embodiment of a temperature profile showing how heat loss to a containment wall located relatively close to the plasma can be reduced;

[0027] **Figure 11** shows one embodiment of a contour plot of a plasma parameter $1/\alpha$ as a function of Y/Λ_e and temperature T;

[0028] **Figure 12** shows one embodiment of a magnetic field profile of an axially directed magnetic field that theta-pinches the plasma;

[0029] **Figure 13** shows examples of different electron and ion distributions in the theta-pinched plasma;

[0030] **Figure 14** shows an example of an E-field profile that results from the different electron and ion distributions of **Figure 13**;

[0031] **Figures 15A-C** show various scales of plasma containment facilitated by electrostatic fields induced by separation of charges;

[0032] **Figure 15D** shows one embodiment of an reversed plasma configuration where the ions are magnetically confined and the electrons are confined by an induced electrostatic field, wherein such a plasma can be scaled to an ion scale length that is substantially greater than the electron scale length;

[0033] **Figures 16A and B** show one embodiment of a Z-pinch plasma containment device that can yield different electron and ion distributions;

[0034] **Figures 17A and B** show one embodiment of a theta-pinch plasma containment device that can yield different electron and ion distributions; and

[0035] **Figure 18** shows one embodiment of a device that can emit various outputs based on a plasma where ion confinement is facilitated by a substantial electrostatic field.

[0036] These and other aspects, advantages, and novel features of the present teachings will become apparent upon reading the following detailed description and upon reference to the accompanying drawings. In the drawings, similar elements have similar reference numerals.

Detailed Description of Some Embodiments

[0037] The present teachings generally relate to systems and methods of plasma confinement at a relatively stable equilibrium. In one aspect, such a plasma includes a substantial internal electrostatic field that facilitates the stability and confinement of the plasma.

[0038] **Figure 1** shows a confined plasma 100 confined by a containment system 112. The plasma 100 defines a first region 102 substantially bounded by a boundary 106, and a second region 104 substantially bounded by the internal boundary 106 and the plasma's boundary. The plasma 100 has at least one dimension on the order of L as indicated by an arrow 110.

[0039] For the purpose of description, the plasma 100 can be characterized as a two-fluid system having an electron fluid and an ion fluid. It will be understood that the ion fluid can involve ions based on the same or different elements and/or isotopes. It will also be understood that the collective fluid-equation of characterization of the plasma herein is simply one way of describing a plasma, and is in no way intended to limit the scope of the present teachings. A plasma can be characterized using other methods, such as a kinetic approach.

[0040] As shown in **Figure 1**, the plasma 100 is depicted as being in an internally non-quasi-neutral stable state, where in the first region 102, the integrated charge due to electrons $Q^-_{\text{first region}}$ is different than the integrated charge due to ions $Q^+_{\text{first region}}$. Similarly in the second region 104, $Q^-_{\text{second region}}$ is significantly different than $Q^+_{\text{second region}}$. The excess charge in the first region 102 is of opposite sign and is approximately equal in magnitude to the excess charge in the second region 104, thereby making the plasma 100, as a whole, substantially neutral.

[0041] As further shown in **Figure 1**, the formation of excess charges of different signs about the internal boundary 106 causes a formation of a bulk internal electrostatic field depicted as arrows 108. If one uses a convention where an E-field points away from a positive charge and towards a negative charge, the E-field 108 would point inward about the boundary 106 if the first region 102 has excess electrons (and the second region 104 has excess ions). Conversely, the E-field 108 would point outward about the boundary 106 if the first region 102 has excess ions. Both possibilities are described below in greater detail.

[0042] As described herein, formation of such electrostatic fields within the plasma 100 contributes to the energy of the plasma system. Determining a relatively-stable energy state of such a system yields plasma parameters, including selected ranges of a plasma dimension *L*, that are substantially different than that associated with conventional plasma systems. It is generally known that static electric fields in a plasma typically do not

exist over a distance substantially greater than the Debye length. They are shielded out because of rearrangements of electrons and ions. This, however, is in the absence of external forces. In the present disclosure described herein, the plasma dimension L is generally greater than many Debye lengths; however this is permitted because of the presence of external forces due to, for example, presence of magnetic fields.

[0043] In the description below, various embodiments of plasma systems are described as cylindrical and toroidal systems. In the present disclosure a cylindrical geometry is used for a simplified description, and is not to be construed as limiting in any manner. Because at least some of the effects described herein depend on the scale of the contained plasma, many arbitrary shapes of a contained plasma can be used in connection with the present disclosure. As an example, the plasma 100 in **Figure 1** is depicted as a "generic" shaped volume manifesting the internal electrostatic field effect by being contained appropriately at a scale on the order of L and given the associated plasma parameters.

[0044] One aspect of the present teachings relates to a method for determining a plasma state that is relatively stable and wherein such stability is facilitated by formation of a relatively substantial internal electrostatic field. **Figure 2** shows one embodiment of a process 120 that determines such a stable state and one or more associated plasma parameters. The process 120 begins at a start state 122, and in a process block 124 that follows, the process 124 characterizes an energy of a plasma system. The energy characterization includes an energy term due to a substantial electrostatic field induced inside the plasma. In a process block 126 that follows, the process 120 determines an equilibrium state associated with a relatively stable energy state of the plasma system. In a process block 128 that follows, the process 120 determines one or more plasma parameters associated with the equilibrium state. The process 120 ends in a stop state 130.

[0045] One way to characterize the energy of the plasma system is to use a two-fluid approach without the quasi-neutrality assumption. In conventional approaches, quasi-neutrality is assumed such that electron and ion density distributions are substantially equal. In contrast, one aspect of the present teachings relates to characterizing the two-fluid system such that the electron and ion densities are allowed to vary independently substantially throughout the plasma. Such an approach allows the two fluids to be distributed differently, and thereby induce a bulk electrostatic field at an equilibrium state of the plasma.

[0046] For a plasma contained at least partially by a magnetic field, the energy U of the system can be expressed as an integral of a sum of an E-field energy term, a B-field energy term, kinetic energy terms of the two fluids, and energy terms associated with pressures of the two fluids. Thus,

$$U = \int \left[\frac{\varepsilon_0 E^2}{2} + \frac{B^2}{2\mu_0} + \sum_s \left(\frac{m_s n_s}{2} u_s^2 + p_s \right) \right] dV \qquad (1)$$

where E represents the electric field strength, ε_o represents the permittivity of free space, B represents the magnetic field strength, μ_o represents the permeability of free space, the summation index and subscripts s denote the species electrons e or ions i, m_s represents the mass of the corresponding species, n_s represents the particle density of the corresponding species, u_s represents the velocity of the corresponding species, p_s represents the pressure of the corresponding species fluid, and dV represents the differential volume element of the volume of plasma.

[0047] For the purpose of description herein, it will be understood that terms "particle density," "number density," and other similar terms generally refer to a distribution of particles. Terms such as "electron density" and "electron number density" generally refer to a distribution of electrons. Terms such as "ion density" and "ion number density" generally refer to a distribution of ion. Furthermore in the description herein, terms such as "average particle density" and "average number density" are used to generally denote an average value of the corresponding distribution.

[0048] One way to further characterize the plasma is to treat the system as being a substantially collisionless and substantially fully-ionized plasma in a steady-state equilibrium. Moreover, each species of the two fluids can be characterized as substantially obeying an adiabatic equation of state expressed as

$$p_s = C_s n_s^{\gamma} \qquad (2)$$

where the C_s represents a constant that can be substantially determined by a method described below, and γ represents the ratio of specific heats of the two species.

[0049] Temperatures associated with the two species can be determined through an ideal gas law relationship

$$p_s = n_s k T_s \qquad (3)$$

where k represents the Boltzmann's constant. Furthermore, both species are assumed to be substantially Maxwellian.

[0050] One way to further characterize the plasma is to express, for each species, a substantially collisionless, equilibrium force balance equation as

$$m_s n_s \boldsymbol{u}_s \cdot \nabla \boldsymbol{u}_s = q_s n_s (\boldsymbol{E} + \boldsymbol{u}_s \times \boldsymbol{B}) - \nabla p_s \tag{4}$$

where m_s represents the particle mass of species s, q_s represents the charge, $\boldsymbol{u}_s$ represents the fluid velocity, and where the anisotropic part of the stress tensor can be and is ignored for simplicity for the purpose of description.

[0051] One way to further characterize the plasma is to express, for the system, Maxwell's equations as

$$\nabla \cdot \boldsymbol{E} = \sum_s q_s n_s / \varepsilon_o ; \tag{5}$$

$$\nabla \times \mathbf{B} = \mu_o \sum_s q_s n_s \mathbf{u}_s ; \tag{6}$$

$$\nabla \times \mathbf{E} = 0; \text{ and} \tag{7}$$

$$\nabla \cdot \mathbf{B} = 0. \tag{8}$$

As is known, Equation (5) is one way of expressing Poisson's equation; Equation (6) is one way of expressing Ampere's law for substantially steady-state conditions; Equation (7) is one way of expressing the irrotational property of an electric field which follows from Faraday's Law for substantially steady-state conditions; and Equation (8) is one way of expressing the solenoidal property of a magnetic field.

[0052] As is also known, Maxwell's equations assume conservation of total charge of a system. Accordingly, one can introduce a dependent variable $\boldsymbol{Q}$ defined as

$$\nabla \cdot \boldsymbol{Q} = n_e \tag{9}$$

to substantially ensure electron conservation by adopting appropriate boundary conditions in a manner described below. The electron density n_e can further be characterized as obeying a relationship $n_e \geq \boldsymbol{0}$.

[0053] One way to determine a relatively stable confinement state of a plasma system is to determine an equilibrium state that arises from a first variation of the energy of the plasma system as expressed in Equation (1) subject to various constraints as expressed in Equations (2)–(9). In one such determination, the pressure term in Equations (1) and (4) can

be eliminated by using Equation (2). The resulting constraints can be adjoined to the resulting energy expression U by using Lagrange multiplier functions. Such a variational procedure generally known in the art can result in a relatively complex general vector form of nonlinear differential equations.

[0054] One way to simplify the variational procedure without sacrificing interesting properties of the resulting solutions is to perform the procedure using cylindrical coordinates and symmetries associated therewith. The cylindrical symmetries can be used to reduce the independent variables of the system to one variable r. Accordingly, dependent variables of the system can be expressed as n_i, n_e, E_r, B_z, B_θ, Q, u_{iz}, $u_{i\theta}$, u_{ez}, and $u_{e\theta}$, where subscripts i and e respectively represent ion and electron species. The first six are state variables. Because derivatives of the last four (velocity components) do not appear in Equations (11A)–(11P) they can be treated as control variables in a manner described below.

[0055] Applying the cylindrical symmetries to the plasma system (where constraints $\nabla\times\mathbf{E}=0$ and $\nabla\cdot\mathbf{B}=0$ of Equations (7) and (8) are substantially satisfied identically), cylindrical coordinate expressions associated with Equations (4)-(6) and (9) can be adjoined to U of Equation (1) using Lagrange multiplier functions M_i, M_e, M_E, M_z, M_θ and M_Q,. As the name implies, variations of the control variables may be considered as producing variations in the state variables as well as in the Lagrange multiplier functions.

[0056] The variation of U leads to first-order differential equations for the state variables and for the Lagrange multiplier functions, and to algebraic equations for the control variables. Such equations can conveniently be expressed as equations in dimensionless form using the following replacements: $r\rightarrow r\Lambda_e$, $u_s\rightarrow u_s c$, $n\rightarrow N_0 n$, $E\rightarrow EeN_0\Lambda_e/\varepsilon_0$, $B\rightarrow BeN_0\Lambda_e\mu_0 c$. $C_s\rightarrow C_s m_e c^2 N_0^{1-\gamma}$, $p_s\rightarrow p_s m_e N_0 c^2$, $Q\rightarrow Q\Lambda_e$ and $T\rightarrow T_s k/mc^2$, where c represents the speed of light, N_0 represents the average particle density, e represents the magnitude of the electron charge, and Λ_e represents the electron skin depth expressed as

$$\Lambda_e = (m_e/\mu_o N_0\, e^2)^{1/2}. \tag{10}$$

[0057] One system of equations that follows from the foregoing energy variation method can be expressed as

$$dM_e/dr = -ru_{ez}^2/2 - M_\theta u_{ez} - ru_{e\theta}^2/2 + M_z u_{e\theta} - M_E - M_Q - C_e r\gamma n_e^{\gamma-1}$$

$$-M_e(C_e\gamma)^{-1}(2-\gamma)n_e^{1-\gamma}(E_r+u_{e\theta}B_z-u_{ez}B_\theta+u_{e\theta}^2/r) \tag{11A}$$

$$dM_i/dr=-ru_{iz}^2/2-M_\theta u_{iz}-ru_{i\theta}^2/2+M_z u_{i\theta}+M_E-C_i r\gamma n_i^{\gamma-1}$$

$$+M_i(C_i\gamma)^{-1}(2-\gamma)n_i^{1-\gamma}(E_r+u_{i\theta}B_z-u_{iz}B_\theta+u_{i\theta}^2/r) \tag{11B}$$

$$dM_E/dr=-rE_r-M_e n_e^{2-\gamma}(C_e\gamma)^{-1}+M_i n_i^{2-\gamma}(C_i\gamma)^{-1}-M_E/r \tag{11C}$$

$$dM_z/dr=-rB_z-M_e n_e^{2-\gamma}u_{e\theta}(C_e\gamma)^{-1}+M_i n_i^{2-\gamma}u_{i\theta}(C_i\gamma)^{-1} \tag{11D}$$

$$dM_\theta/dr=-rB_\theta+M_e n_e^{2-\gamma}u_{ez}(C_e\gamma)^{-1}-M_i n_i^{2-\gamma}u_{iz}(C_i\gamma)^{-1}+M_\theta/r \tag{11E}$$

$$dM_Q/dr=M_Q/r \tag{11F}$$

$$u_{ez}=\left\{M_e n_e^{1-\gamma}B_\theta(C_e\gamma)^{-1}-M_\theta\right\}/r \tag{11G}$$

$$u_{e\theta}=\left\{M_z-M_e n_e^{1-\gamma}(rC_e\gamma)^{-1}\right\}/\left\{r+2M_e n_e^{1-\gamma}(rC_e)^{-1}\right\} \tag{11H}$$

$$u_{iz}=\left\{M_i n_i^{1-\gamma}B_\theta(C_i\gamma)^{-1}-M_\theta\right\}/r \tag{11I}$$

$$u_{i\theta}=\left\{M_z-M_i n_i^{1-\gamma}(rC_i\gamma)^{-1}\right\}/\left\{r+2M_i n_i^{1-\gamma}(rC_i)^{-1}\right\} \tag{11J}$$

$$dn_e/dr=-(C_e\gamma)^{-1}n_e^{2-\gamma}(E_r+u_{e\theta}B_z-u_{ez}B_\theta-u_{e\theta}^2/r) \tag{11K}$$

$$dn_i/dr=(C_i\gamma)^{-1}n_i^{2-\gamma}(E_r+u_{i\theta}B_z-u_{iz}B_\theta+u_{i\theta}^2/r) \tag{11L}$$

$$dE_r/dr=-E_r/r+n_i-n_e \tag{11M}$$

$$dB_z/dr=n_e u_{e\theta}-n_i u_{i\theta} \tag{11N}$$

$$dB_\theta/dr=-B_\theta/r+n_i u_{iz}-n_e u_{ez} \tag{11O}$$

$$dQ/dr=-Q/r+n_e \tag{11P}$$

[0058] One set of boundary conditions (at $r=0$ and $r=a$, where a is defined as an outer boundary in **Figure 3**) includes $E_r(0)=E_r(a)=0$, $B_z(a)=B_0$, and $B_\theta(0)=0$. Boundary conditions can further include $Q(0)=0$ and $Q(a)=N_0 a/2$ relating to charge conservation for individual species. Conditions at each boundary can further be imposed on each state variable or its corresponding Lagrange multiplier function so as to be substantially equal to zero if there is substantially no state-variable condition. It follows that $M_e(0)=M_e(a)=M_i(0)=M_i(a)=M_z(0)=0$.

[0059] In one implementation of a method for determining a stable equilibrium of the foregoing cylindrical plasma system, input parameters (expressed in dimensional form) for solving the system of equations (Equations (11A-P)) include the cylindrical radius a, the average particle number density N_0 substantially equal for both species, the axial magnetic field at the boundary a such that $B_z(a) = B_0$, the net axial current I, and a temperature value T_0 for both electrons and ions that is the temperature taken at that value of r at which $n_s = N_0$. Using these input parameters, one can determine that $B_\theta(a)=\mu_0 I/(2\pi a)$.

[0060] Furthermore, the values of C_s can be determined by combining the adiabatic equation of state from Equation (2) and the ideal gas law from Equation (3) so as to yield $C_s = n_s^{1-\gamma} kT_s$. Thus, $C_s = N_0^{1-\gamma} kT_0$ when evaluated at the value of r where $n_s=N_0$ and $T_s=T_0$. The electron and ion average temperatures may be different, which would result in different values of C_i and C_e. For the examples of the present disclosure, they are taken to be substantially the same, i.e., T_0. Such a simplification for the purpose of description should not be construed to limit the scope of the present teachings in any manner.

[0061] Another useful set of input parameters can be obtained by replacing B_0 with a plasma beta value defined as $\beta = N_0 kT_0/(B_0^2/2\mu_0)$ and by replacing I with another beta value $\alpha = N_0 kT_0/(B_\theta(a)^2/2\mu_0)$, where $I = 2\pi a B_\theta(a)/\mu_0$. Note that $1/\beta = 0$ corresponds to a substantially pure Z-pinch, and $1/\alpha = 0$ corresponds to a substantially pure theta-pinch. A screw-pinch corresponds to substantially nonzero values for both $1/\alpha$ and $1/\beta$.

[0062] The foregoing energy variational method yields a description of the plasma system by twelve first-order coupled nonlinear ordinary differential equations, four algebraic equations, and one inequality condition ($n_e \geq 0$), with sixteen unknowns. Numerical solutions to such a system of equations can be obtained in a number of ways. Solutions disclosed herein are obtained using a known differential equation solving routine such as BVPFD that is part of a known numerical analysis software IMSL.

[0063] **Figure 3** now shows one embodiment of a cylindrically shaped contained plasma 140 that embodies a possible solution to the energy variation analysis of the two-fluid system described above. As a reference, the cylindrical plasma 140 is superimposed with a cylindrical coordinate system 142. An arbitrary point 144 on the coordinate system 142 can be expressed as having coordinates (r, θ, z).

[0064] The plasma 140 defines a first cylindrical volume 150 extending from the Z-axis to $r = Y$, and a second cylindrical volume 152 extending from the Z-axis to $r = a$. The first volume 150 generally corresponds to a region of the plasma 140 where the first species of the two fluids is distributed as $n_1(r)$. The second volume 152 generally corresponds to a region of the plasma 140 where the second species of the two fluids is distributed as $n_2(r)$.

[0065] In general, the first and second species are distributed such that

$$\int_0^Y n_1 dr > \int_0^Y n_2 dr, \tag{12A}$$

$$\int_Y^a n_1 dr = 0, \tag{12B}$$

$$\int_0^a n_1 dr = \int_0^a n_2 dr. \tag{12C}$$

That is, the first region 150 has more of the first species than the second species, and the portion of the second region 152 outside of the first region has substantially none of the first species. As Equation (12C) shows, the total number of particles in the two species is substantially the same in one embodiment.

[0066] In some embodiments, substantially all of the first species is located within the first region 150 such that $r = Y$ defines a boundary for the first species. Consequently, the region $Y < r < a$ has substantially none of the first species, and is populated by the second species by an amount ΔN. Since the total numbers of the first and second species are substantially the same in one embodiment, the value of ΔN is also representative of the excess number of the first species relative to the second species in the first region 150.

[0067] In some embodiments, as described below in greater detail, the first species can be the electrons, and the second species the ions when a plasma is contained within one or more selected ranges of value for the boundary $r = Y$. In other embodiments, as also described below in greater detail, the first species can be the ions, and the second species the electrons when the plasma is contained in one or more other selected ranges of value for the boundary $r = Y$.

[0068] **Figures 4A and B** show two methods of confining a cylindrical geometry plasma by magnetic fields, thereby causing the electron and ion distributions to become different in a manner described above in reference to **Figure 3**. **Figure 4A** shows one embodiment of a Z-pinch confinement 160, and **Figure 4B** shows one embodiment of a theta-pinch confinement 180. Although the Z-pinch and theta-pinch methods are shown separately, it will be understood that these two pinches can be combined to form what is commonly referred to as a screw-pinch.

[0069] As shown in **Figure 4A**, the Z-pinch 160 can be achieved when an axial current I_Z 164 is established in a plasma 172. Such a current can be established in a number of ways, including an example method described below. The axial current I_Z 164 causes formation of an azimuthal magnetic field B_θ 166 that asserts a radially inward force $F_{Z\text{-}pinch}$ 168 on the moving charged particles of the plasma 162.

[0070] As described below in greater detail, when the radial dimension of the plasma is selected in certain ranges, motion of one species relative to the other species can be enhanced and thereby be more subject to the magnetic pinching force. Thus, as shown in **Figure 4A**, an inner first region 170 of the plasma 162 includes substantially all of the magnetically contained species. In **Figure 4A**, the magnetically confined species is depicted as being the electrons. As such, the ions are distributed within a second region 172 that includes and radially extends beyond the first region 170. Such a distribution of the two species can induce a substantial internal electrostatic field 174 denoted as E'_r. The electrostatic field 174 facilitates containment of the ions substantially within the second region 172. It will be understood that if the ions are made to be magnetically confined within the first region 170, the electrostatic field 174 is reversed in direction, and the electron confinement can be facilitated by such an electrostatic field.

[0071] As shown in **Figure 4B**, the theta-pinch 180 can be achieved when a steady azimuthal current I_θ 186 is established in the plasma. The current I_θ 186 can be produced in a number of ways including an example method described below. The axial magnetic field B_Z 184 asserts a radially inward force $F_{\theta\text{-}pinch}$ 188 on the azimuthal current I_θ 186 and thereby facilitates containment of the plasma 182.

[0072] **Figure 5** now shows that a plasma confinement solution described above in the context of cylindrical geometry can be used to approximate a design of a toroidal

geometry containment device. A section of a toroidally confined plasma 200 is shown superimposed with a section of a similarly dimensioned (tube dimension) cylindrically confined plasma 210. The toroid 200 is depicted to be centered about a center point 206 such that the center of the toroidal "tube" (having a radius a) is separated from the center point 206 by a distance R (indicated by arrow 208).

[0073] One can see that when the distance R is relatively large compared to a, such as in a high aspect ratio (R/a) toroid, a given segment of the toroid geometry can be approximated by the cylindrical geometry. Thus, one can obtain design parameters using a cylindrical geometry, and apply such a solution to designing of a toroidal device. As is known in the art, such a cylindrical approximation provides a good base for a toroidal design. One way to correct for the differences between the toroidal and cylindrical geometries is to provide a corrective external field, often referred to as a vertical field that inhibits the plasma toroid radius R from increasing due to magnetic hoop forces, to confine the plasma.

[0074] Thus as shown in **Figure 5**, a toroidally confined plasma 200 includes a toroidally shaped first region 202 and a toroidally shaped second region 204 that are arranged with respect to each other in a manner similar to that of a cylindrical plasma. As with the cylindrical plasma, the first region may be defined by electrons in some embodiments, and also by ions in other embodiments.

[0075] The foregoing analysis of the cylindrical plasma includes a one-dimensional (r) analysis using the energy variation method. As described above in reference to **Figure 5**, such one-dimensional analysis can provide a basis for estimating the design and characterization of a high aspect ratio toroid. A more generalized three-dimensional analysis of, for example, a general toroid or a chamber of any shape, in a similar manner is expected to yield similar results where parts of the electrons and ions separate, thereby causing a substantial electrostatic field within the plasma.

[0076] One aspect of the present teachings relates to a scale of a contained plasma having a substantial electrostatic field induced therein. Various results of the foregoing energy variational procedure are described in the context of cylindrical symmetry. It will be appreciated, however, that such results can also be manifested in other shapes of contained plasma having a similar scale.

[0077] **Figures 6 - 10** show various plasma parameters that result from the cylindrically symmetric energy variational analysis for a Z-pinched system with a set of inputs. The plasma is defined as a cylinder having an outer diameter a of approximately three times the skin depth (scale length) Λ_e. With such a selection of the scale of the plasma, example input parameters include $N_0 = 10^{19}/\mathrm{m}^3$, $T_0 = 5$ keV, $1/\alpha = 2.51$ (thereby defining the magnetic field strength $B_\theta(a)$ and the axial current I), and $1/\beta = 0$ (thereby setting $B_z(a) = B_0 = 0$). The corresponding electron skin depth parameter $\Lambda_e = (m_e/\mu_o N_0\, e^2)^{1/2}$ (Equation (10), and depending on the input parameter N_0) is approximately 1.7 mm.

[0078] The foregoing input parameters result in a contained plasma where the electrons are pinched by magnetic forces thereby giving rise to electron-ion charge separation. Consequently, the electrons are distributed substantially within the inner region of the cylinder (first region 150 in **Figure 3**), and the ions are distributed partially in the first region 150 and partially beyond the boundary ($r=Y$) of the first region 150. Such a charge separation produces a static electric field that confines the ions. The resulting charge gradient scale length is relatively small – on the order of the electron skin depth as expressed in Equation (10).

[0079] **Figure 6** shows a profile 220 of the azimuthal magnetic field strength B_θ as a function of a dimensionless variable r/Λ_e. Such a magnetic field confines the electrons as shown in **Figure 7**, where the forces acting on the electrons are shown as a function of r/Λ_e. In the force profile of **Figure 7**, a positive value of a force is indicative of a radially outward directionality, and a negative value the opposite. Thus, a kinetic pressure force 230 that tends to make the electron fluid want to expand is directed outward. An electrical force 232 on the electrons is caused by the inwardly directed electrostatic field induced in the plasma by the foregoing charge gradient. A magnetic force 234 that confines the electrons is thereby directly inward, and offsets the sum of outwardly directed pressure and electrical forces 230, 232 over much of the electron volume. In the example electron confinement shown in **Figure 7**, the pressure and electrical forces 230 and 232 have substantially similar magnitudes over much of the electron volume. In one embodiment shown in **Figure 7**, the electron forces profiles do not extend beyond $r=Y$ because there are substantially no electrons beyond that boundary.

[0080] **Figure 8** shows profiles of forces acting on the ions. A magnetic force 242 on the ions is substantially negligible due to the relatively low velocity of the moving ions. A kinetic pressure force 240 that tends to make the ion fluid want to expand is directed outward. An electrical force 244 on the ions is directed inward, and is caused by the inwardly directed electrostatic field induced in the plasma by the foregoing charge gradient. One can see that the electrical force 244 is significant and generally offsets the pressure force 240. Thus, the electric field produced from the charge separation is the primary ion confining force.

[0081] It will be appreciated that while the magnetic field provides an initial confinement mechanism for the plasma, the internally-produced electric field plays an important and substantial role in establishing a stable plasma equilibrium. The force profiles shown in **Figures 7 and 8** and the resulting steady-state equilibrium of the plasma underscore the importance of the electric field. Such a stable equilibrium state facilitated by the electric field does not appear if the plasma is quasi-neutral. Hence, the importance of not making the quasi-neutrality assumption in designing a plasma containment device is demonstrated.

[0082] **Figure 9A** now shows an electron distribution 250 and an ion distribution 254 that give rise to an electric field profile 252. The three curves 250, 252, and 254 are shown as functions of a dimensionless variable r/Λ_e. The vertical scale for the electron and ion distributions 250 and 254 is in terms of the average density value N_0. The electric field profile 252 gives rise to the electrical force profiles described above in reference to **Figures 7 and 8**. As the electron distribution 250 shows, the electrons are distributed substantially within the boundary Y at approximately $1.2\Lambda_e$. As defined in Equation (10), the value of $\Lambda_e = (m_e/\mu_o N_0\, e^2)^{1/2}$ is approximately 1.7 mm when $N_0 = 10^{19}/\text{m}^3$. Thus, the value of the electron boundary Y for the example plasma of **Figure 9A** is approximately 2.04 mm.

[0083] As shown in **Figure 9A,** the electron and ion distributions overlap over at least a portion of the plasma about the axis. As further shown in **Figure 9A,** the electrons are substantially confined to a restricted volume defined by the electron boundary Y. Thus, such a restricted volume can be characterized by a volume scale length such as the electron skin depth Λ_e.

[0084] As further shown in **Figure 9A**, the ion distribution 254 extends beyond the boundary Y. Beyond the Y boundary, the ion fluid can be characterized as satisfying single fluid equations that can easily be obtained by modifying the set of equations described above. One way to obtain a substantially complete ion distribution and its associated plasma parameter(s) is to match the two sets of equations ($r<Y$ and $r>Y$) at the boundary Y by adjusting input parameters until the dependent variables and their derivatives are substantially continuous at Y.

[0085] One aspect of the present teachings relates to a plasma system having an induced separation of charges, as shown by the electron and ion distributions 250 and 254, thereby causing formation of the radially directed electric field profile 252 that substantially overlaps with the plasma volume. Such a coverage of the induced electrostatic field can be achieved in contained plasma systems where the boundary Y for electrons has a dimension on the order of the electron scale length Λ_e.

[0086] For a system to lie within an energy well sufficiently deep to provide a robust confinement for one embodiment, the cylinder radius can lie within a range near the value of the electron scale length (skin depth) Λ_e. In the example embodiment described above in reference to **Figures 6-9**, Y $1.2\Lambda_e$, and the electric field extends over a substantial portion of the plasma.

[0087] A relatively large radius configuration (e.g., $Y=6\Lambda_e$) can result in a substantial electric field being induced near the outer region of the plasma cylinder. An energy well associated with such a configuration can be relatively shallow when compared to the Y $1.2\Lambda_e$ case. Also, a relatively small radius configuration (e.g., $Y=0.3\Lambda_e$) can result in confinement being lost.

[0088] Thus in one embodiment, a plasma confinement that is facilitated by the induced electrostatic field has a value of Y that is in a range of approximately 1 to 2 times the electron scale length Λ_e. In one embodiment, a value of Y around $1.2\Lambda_e$ appears to provide a near optimal confinement condition. For a plasma with $N_0 = 10^{19}/m^3$ (as with the example plasma of **Figures 6-9**), $\Lambda_e = 1.7$ mm, and $Y = (1.2)(1.7)$ 2.04 mm. Since $a = 3\Lambda_e$ for the example plasma, the outer radius of the contained plasma is approximately 5.1 mm. One can

see that such a compact dimension of a stable, contained plasma can be used in a number of applications, some of which are described below in greater detail.

[0089] The plasma is contained such that energy and/or particle loss(es) from the plasma to a wall defining a containment volume is reduced. One way to achieve such energy/particle loss reduction is to reduce the number of plasma particles coming into contact with the wall. As shown in **Figure 9B**, where the electron and ion distributions 250 and 254 are plotted on a logarithmic scale, the ion number density 254 reaches a value of approximately 0.001 N_0 when r/Λ_e is approximately twice the value of Y. Thus for an embodiment where $Y = 1.2\Lambda_e$ 2.04 mm, the ion number density reaches approximately 0.1% of the average density value N_0 at r $(2.04)(2) = 4.1$ mm.

[0090] As described above, for a plasma containment design where $a = 3\Lambda_e$, the outer radius a is approximately 5.1 mm for the $Y = 1.2\Lambda_e$ case. For such a system, a wall can be positioned at a location $r > 5.1$ mm and still allow construction of a relatively small containment device. Moreover, the ion number density at $r > 5.1$ mm ($3\Lambda_e$) is substantially lower than the 0.1% level described above. Thus, the number of ions coming into contact with the wall at $r > 5.1$ mm and transferring energy thereto and/or interacting therewith is reduced even more.

[0091] **Figure 10** shows a plasma temperature profile 260 as a function of r/Λ_e for the example plasma described above in reference to **Figures 6–9**. One can see that the temperature is reduced substantially at $3\Lambda_e$ (5.2 mm). The temperature is even lower for the region $r > 3\Lambda_e$. Thus, heat transfer from the plasma to the wall located at $r > 3\Lambda e$ is reduced, since the plasma particles that come into contact with the wall have substantially low kinetic energies when compared to the inner portion of the plasma.

[0092] The example plasma described above in reference to **Figures 6-10** advantageously includes the induced electrostatic field. Such a plasma includes electrons distributed substantially within a boundary Y that is in a range of approximately 1-2Λ_e so as to allow the electric field to cover a substantial portion of the plasma volume. Such a significant presence of the electric field facilitates a robust containment of the plasma at a scale on the order of the electron scale length (skin depth). Investigation of such a plasma system shows that such features of the contained plasma at such a scale hold when the input

parameters are varied significantly. As an example, similar advantageous electric field facilitated confinement holds within a factor of approximately 2 when the average number density N_0 changes by a factor of approximately 10 and when the input temperature value T_0 changes by a factor of approximately 30. Thus, design of a plasma containment having a dimension on the order of electron scale length can be made relatively flexible.

[0093] The present disclosure reveals substantial electric fields due to excess electrons in the $r<Y$ region and ions being substantially the only species in the $r>Y$ region. As described above, numerical solutions can be obtained by solving Equations (11A)-(11P) for $r<Y$ and substituting Y for a in the boundary conditions. One can solve the modified set (for ions) for $r>Y$ and replacing 0 by Y in the boundary conditions and then matching the solutions of the two sets at $r=Y$. In one embodiment, the number density of the magnetically bound species becomes substantially zero at $r=Y$.

[0094] In one embodiment, accomplishing such a matching process can place an additional restriction on the input or control parameters that can be expressed in terms of $1/\alpha$ and $1/\beta$. For example, in the cylindrical coordinate treatment of the Z-pinch embodiment, $1/\alpha$, which can be obtained from N_0, T_0, and B_0, is approximately 2 (for typical fusion plasma parameter values). A more precise value of $1/\alpha$ can be expressed as a slowly varying function of T_0 and n_0. For the example cylindrical geometry, an approximate value can be obtained from an example contour plot of $1/\alpha$ as a function of Y/Λ_e and temperature T, such as that of **Figure 11**. For a theta-pinch, screw-pinch, ions moving, other geometries, or combinations thereof, the appropriate restriction can be obtained either experimentally or by solving the equations similar to Equations (11A)-(11P) and the appropriate modified set for $r>Y$. In one embodiment, the number density of the current carrying species approaches approximately zero at the boundary $r=Y$. In one embodiment where both species can carry substantial current, similar method can be applied to obtain a solution.

[0095] The example plasma described above in reference to **Figures 6-10** is Z-pinched. Similar electrostatic field effects can also arise when a plasma is theta-pinched. **Figures 12-14** shows an example result of the energy variational method described above.

[0096] For the theta-pinch example, an outer diameter a of approximately $3\ \Lambda_e$ is used. Furthermore, input parameters $N_0 = 10^{19}/\text{m}^3$, $T_0 = 10^4$ keV, $1/\alpha = 0$, and $1/\beta = 20.5$ are used. The corresponding electron scale length $\Lambda_e = (m_e/\mu_o N_0\, e^2)^{1/2}$ is approximately 1.7 mm.

[0097] Based on the foregoing example inputs, **Figure 12** shows an axial magnetic field profile 270 as a function of distance from the Z axis. Such a magnetic field theta-pinch can confine the plasma such that an electron distribution 280 and an ion distribution 282 are formed as shown in **Figure 13**. Separation of charges due to such distributions can cause a substantial electrostatic field profile 290 as shown in **Figure 14**.

[0098] The foregoing example theta-pinch confinement results in the value of Y being approximately 2.04 mm. Thus, a theta-pinched plasma with a confinement dimension on the order of the electron scale length Λ_e can provide the various advantageous features described above in reference to the Z-pinched plasma system.

[0099] As previously described, a screw-pinch can be achieved by a combination of Z and theta pinches. Thus, an energy variational analysis similar to the foregoing can be performed with $1/\alpha$ 0 and $1/\beta$ 0 to yield similar results where a substantial electrostatic field is induced by separation of charges. Furthermore, a screw-pinched plasma with a confinement dimension on the order of the electron scale length Λ_e can provide similar advantageous features described above in reference to Z and theta pinched plasma systems. Screw-pinch magnetically confined plasmas are generally regarded as more stable than simple Z- or theta-pinches. It is expected that screw-pinch embodiments of the present teachings will share the various features disclosed herein.

[0100] As also described, magnetically confining a plasma in a dimension on the order of the plasma's electron scale length results in separation of charges, thereby inducing a substantial electrostatic field over a substantial portion of the plasma volume. Such an electric field can be characterized so as to correspond to a depth of an energy well associated with a stable equilibrium. Moreover, the energy well depth is expected to be relatively deep when the electron fluid radius Y is in a range of approximately $1 - 2\ \Lambda_e$. Such relatively deep energy well of the equilibrium provides a relatively stable confined plasma. Such stability of a confined plasma at a value of Y of approximately $1 - 2\ \Lambda_e$, however, does not preclude a

possibility that magnetic confinement at larger values of Y can have its stability facilitated significantly by the induced electrostatic field.

[0101] One aspect of the present teachings relates to a magnetically confined and relatively stable equilibriated plasma at different dimensional scales. **Figures 15A-C** show electron and ion distributions for different plasma sizes. While the larger sized plasma systems may not yield equilibria that are as stable as the case where $Y = 1 - 2\ \Lambda_e$, such equilibria may nevertheless have sufficient stabilities that are facilitated by the electric field.

[0102] **Figure 15A** shows a first set of particle densities as a function of the dimensionless variable r/Λ_e. Curves 300 and 302 represent example electron and ion distributions. The electron distribution 300 is depicted as being substantially bounded at Y $1.5\Lambda_e$, and is thereby similar to the example plasma described above in reference to **Figure 9A**. A resulting induced electrostatic field (indicated as a bracket 304) covers a substantial portion of the plasma.

[0103] **Figure 15B** shows a second set of particle densities where an electron density distribution 306 is substantially bounded at an example value of Y $10\Lambda_e$. An ion density distribution 308 is shown to extend beyond the boundary Y, thereby inducing an electrostatic field that influences a region 310 near the outer boundary of the plasma.

[0104] **Figure 15C** shows a third set of particle densities where an electron density distribution 312 is substantially bounded at an example value of Y $40\Lambda_e$. An ion density distribution 314 is shown to extend beyond the boundary Y, thereby inducing an electrostatic field that influences a region 316 near the outer boundary of the plasma.

[0105] In various plasma embodiments, the electric field coverage scales (304, 310, 316) are generally similar, and can be on the order of few electron scale lengths. Thus, one way to characterize a role of the electrostatic field in the stability of the plasma is to consider the electric field as a layer formed near the surface of the plasma volume. In systems where a plasma volume dimension (e.g., radius a in cylindrical systems) is on the order of the E-field layer "thickness" (such as the system of **Figure 15A**), the influence of the electrostatic field is substantial with respect to the overall plasma. Consequently, an energy stability facilitated by the electrostatic field can be more pronounced in such systems.

[0106] In systems where a plasma volume dimension is substantially larger than the E-field layer "thickness" (such as the systems of **Figures 15A and B**), the influence of the electrostatic field may not be as substantial when compared to systems such as that of **Figure 15A**. Consequently, electrostatic fields can provide significant contributions to energy stabilities; however, such contributions are typically not expected to be as pronounced as that of a smaller system.

[0107] One aspect of the present teachings relates to a plasma having a substantially larger scale length (skin depth) than that of plasmas where the induced electrostatic field is on the order of an electron scale length (electron skin depth). **Figure 15D** shows an example plasma 400 having an ion distribution bounded at an inner boundary 402 and an electron distribution bounded at an outer boundary 404, thereby inducing an electrostatic field 406 that points radially outward. One can see that in such a plasma, roles of the electrons and ions are reversed.

[0108] In such a role-reversed plasma, ions act as charge carriers, thereby being subject to magnetic confinement. The value of a for the ions-moving plasma would be many times that for the electrons-moving plasma because of the much larger ion skin depth $\Lambda_{ion} = (m_{ion}/\mu_o N_0 e^2)^{1/2}$. For plasmas having a similar average density value, the ratio of $\Lambda_{ion}/\Lambda_e = (m_{ion}/ m_e)^{1/2}$. For deuterium, the ratio Λ_{ion}/Λ_e is approximately 61. Thus, a plasma having moving ions would have a volume of approximately 61^2=3700 times that of the similar electrons-moving plasma, all else being substantially the same. The energy variational method described herein can be modified readily for analysis, and a resulting plasma system likely would be sufficiently large to allow power production.

[0109] As described above in connection with **Figures 1-15**, the induced electrostatic field can form in a plasma having a wide range of volume scale length. For a plasma where the electrons are magnetically confined, the volume scale length can represented by the electron confinement dimension Y. In one embodiment, the volume scale length can range from approximately 1 Λ_e to approximately 1000 Λ_e. In one embodiment, the volume scale length can range from approximately 1 Λ_e to approximately 100 Λ_e. In one embodiment, the volume scale length can range from approximately 1 Λ_e to approximately 60 Λ_e. In one embodiment, the volume scale length can range from approximately 1 Λ_e to

approximately 40 Λ_e. In one embodiment, the volume scale length can range from approximately 1 Λ_e to approximately 10 Λ_e. In one embodiment, the volume scale length can range from approximately 1 Λ_e to approximately 2 Λ_e. Similar volume scale length characterization can be applied to the plasma where the ions are confined.

[0110] As described above in connection with **Figures 1-15**, the induced electrostatic field formed in the plasma facilitates formation of a stable plasma state. In particular, the electrostatic field comprises a radially directed field. As is known, dynamic (as opposed to static) radial electric fields are known to exist in large systems such as tokamaks. However, such dynamic radial fields are not due to the significant separation of the charges. Rather, such dynamic radial fields are the result of imbalances in the ion Lorentz and ion pressure forces, and the dynamic field magnitudes appear to be smaller than the magnitudes of induced static electric field (by charge separation) by a factor of roughly 10.

[0111] As described above in connection with **Figures 1-15**, electrostatic field-facilitated stable plasma can be formed by magnetic confinement of electrons or ions. In such configurations, the magnetically confined particles act as charge carriers. Thus, when electrons act as charge carriers, electrons are magnetically confined; when ions act as charge carriers, ions are magnetically confined.

[0112] Being a charge carrier in the plasma can be characterized in different ways. One way is to say that charge carriers cause a current in the plasma. Another way is to say that charge carriers undergo a bulk motion in the plasma. Yet another way is to say that charge carriers flow in the plasma.

[0113] In one embodiment, both the electrons and the ions can act as charge carriers. That is, both the electrons and the ions can contribute to the current, undergo bulk motions, and flow in the plasma. A difference in the degrees of a current-producing characteristic of the two species can give rise to one species being confined magnetically more than the other. Such a difference in the magnetic confinements of the two species can induce a charge separation that causes formation of an electrostatic field in the plasma.

[0114] **Figures 16 and 17** now show simplified diagrams of plasma containment devices that can magnetically contain a plasma having the substantial electrostatic field

induced therein. **Figures 16A and B** show a simplified Z-pinch device 320 having a containment ring 322 magnetically coupled to a primary winding 324 via a core 326. Charge carriers in the ring 322 act as a secondary winding on a transformer core 326, such that a primary current $i_1(t)$ established in the primary winding 324 (via a power supply 334) induces a secondary current $i_2(t)$ 332 within the ring 322. Such a toroidal current (an axial current in the cylindrical approximation) confines the plasma as described above in reference to **Figure 4A**. Appropriately selected dimension of the ring 322 and appropriately selected parameters for plasma therein results in the separation of an electron density distribution 330 from an ion density distribution 328, thereby inducing the substantial electrostatic field.

[0115] **Figures 17A and B** show a simplified theta-pinch device 340 having a containment section 342 with a winding 344 thereabout. A current $i(t)$ can be generated by a power supply 346 and be passed through the winding 344, thereby forming an axial magnetic field B_Z 352 (toroidal field in a toroidal system). As described above in reference to **Figure 4B**, such a magnetic field can confine the plasma via a theta-pinch. Appropriately selected dimension of the confinement section 342 and appropriately selected parameters for plasma therein can result in the separation of an electron density distribution 350 from an ion density distribution 348, thereby inducing the substantial electrostatic field.

[0116] As previously described, the Z- and theta-pinches can be combined to yield a screw-pinch. Thus, the Z and theta pinch devices of **Figures 16 and 17** can be combined to yield a screw-pinch device. Furthermore, such confinement methods and various concepts disclosed herein can be implemented in any containment devices having a confinement section that can be approximated by a cylindrical geometry.

[0117] **Figure 18** now shows one embodiment of a fusion reaction apparatus 360 that can based on a contained plasma of the present teachings. The reaction apparatus 360 includes a reaction chamber 364 that includes a magnetic field that confines a plasma 372 substantially within the reaction chamber 364. Such a magnetic field can be generated by a confinement field generator component 366 that is electromagnetically coupled to the plasma 372. The field generator component 366 is powered by a power supply 370. The reaction apparatus 360 further includes a reaction fuel supply that provides and/or maintains a reaction fuel for the plasma 372.

[0118] As shown in **Figure 18**, the plasma 372 embodies an electron distribution 374 that is at least partially separated from an ion distribution 376. Such a contained plasma allows at least the reaction chamber 364 to have a relatively small dimension as described above.

[0119] The plasma 372 contained in the foregoing manner can undergo a nuclear fusion reaction that can yield neutrons, x-rays, power, and/or other reaction products. Some of the possible reaction configurations and products for an example deuterium-tritium (DT) reaction at various example operating conditions are summarized in Tables 1 – 3.

[0120] Table 1 summarizes various dimensions associated with an electron-scaled high aspect ratio toroidal system at various particle densities. Quantities associated with Table 1 are defined as follows: n = average particle density; Λ = electron scale length; Y = electron fluid boundary radius = set to 1.5Λ; a = toroid's minor radius = ion fluid boundary radius = set to $2.5Y$; R = toroid's major radius = set to $20a$; V = toroid's volume = $2\pi^2 Ra^2$.

n (m^{-3})	1.00×10^{19}	1.00×10^{20}	1.00×10^{21}	1.00×10^{22}	1.00×10^{23}
Λ (cm)	1.68×10^{-1}	5.32×10^{-2}	1.68×10^{-2}	5.32×10^{-3}	1.68×10^{-3}
Y (cm)	2.52×10^{-1}	7.98×10^{-2}	2.52×10^{-2}	7.98×10^{-2}	2.52×10^{-2}
a (cm)	6.31×10^{-1}	2.00×10^{-1}	6.31×10^{-2}	2.00×10^{-2}	6.31×10^{-3}
R (cm)	1.26×10^{1}	3.99×10^{0}	1.26×10^{0}	3.99×10^{-1}	1.26×10^{-1}
V (cm^3)	9.90×10^{1}	3.13×10^{0}	9.90×10^{-2}	3.13×10^{-3}	9.90×10^{-5}

Table 1

[0121] Table 2 summarizes various neutron production rate estimates with the system of Table 1 at various temperatures. Quantities associated with Table 2 are defined as follows: T = plasma temperature; σv = reaction rate; neutron rate = $n^2(\sigma v)V/4$. These reaction rate and neutron rate expressions are well known in the art.

T (keV)	σv (cm^3/s)	Neutron rate (s^{-1})				
		n=10^{19} m^{-3}	n=10^{20} m^{-3}	n=10^{21} m^{-3}	n=10^{22} m^{-3}	n=10^{23} m^{-3}

1	5.50×10^{-21}	1.36×10^{7}	4.30×10^{7}	1.36×10^{8}	1.36×10^{8}	1.36×10^{9}
2	2.60×10^{-19}	6.44×10^{8}	2.03×10^{9}	6.44×10^{9}	2.03×10^{10}	6.44×10^{10}
5	1.30×10^{-17}	3.22×10^{10}	1.02×10^{11}	3.22×10^{11}	1.02×10^{12}	3.22×10^{12}
10	1.10×10^{-16}	2.72×10^{11}	8.61×10^{11}	2.72×10^{12}	8.61×10^{12}	2.72×10^{13}
20	4.20×10^{-16}	1.04×10^{12}	3.29×10^{12}	1.04×10^{13}	3.29×10^{13}	1.04×10^{14}
50	8.70×10^{-16}	2.15×10^{12}	6.81×10^{12}	2.15×10^{13}	6.81×10^{13}	2.15×10^{14}
100	8.50×10^{-16}	2.10×10^{12}	6.65×10^{12}	2.10×10^{13}	6.65×10^{13}	2.10×10^{14}

Table 2

[0122] Table 3 summarizes various power production estimates with the system of Table 1 at various temperatures for a deuterium-tritium device. Quantities associated with Table 3 are defined as follows: T = plasma temperature; power associated with charged particles = $(n_D n_T \sigma v)(5.6 \times 10^{-13})$ (Watts). The power expression is well known in the art.

T (keV)	Power (W)				
	$n=10^{19}$ m^{-3}	$n=10^{20}$ m^{-3}	$n=10^{21}$ m^{-3}	$n=10^{22}$ m^{-3}	$n=10^{23}$ m^{-3}
1	7.62×10^{-6}	2.41×10^{-5}	7.62×10^{-5}	2.41×10^{-4}	7.62×10^{-4}
2	3.60×10^{-4}	1.14×10^{-3}	3.60×10^{-3}	1.14×10^{-2}	3.60×10^{-2}
5	1.80×10^{-2}	5.70×10^{-2}	1.80×10^{-1}	5.70×10^{-1}	1.80×10^{0}
10	1.52×10^{-1}	4.82×10^{-1}	1.52×10^{0}	4.82×10^{0}	1.52×10^{1}

20	5.82×10^{-1}	1.84×10^{0}	5.82×10^{0}	1.84×10^{1}	5.82×10^{1}
50	1.21×10^{0}	3.81×10^{0}	1.21×10^{1}	3.81×10^{1}	1.21×10^{2}
100	1.18×10^{0}	3.72×10^{0}	1.18×10^{1}	3.72×10^{1}	1.18×10^{2}

Table 3

[0123] As an example from Tables 1-3, not to be construed as limiting in any manner, consider a plasma system having a DT fuel confined in a high aspect ratio toroidal chamber. An average number density n of approximately 10^{20} m^{-3} corresponds to an electron scale length Λ of approximately 0.0532 cm. Setting $Y=1.5\Lambda_e = 0.080$ cm, the minor radius a at $2.5\,\Lambda_e = 0.20$ cm, the major radius R at $20a = 4$ cm results in a volume V of approximately 3.13 cm^3.

[0124] Operating such a plasma at a temperature of approximately 5 keV (where the reaction rate is approximately $1.30\text{x}10^{-17}$) can yield approximately 1.02×10^{11} neutrons per second. Neutron fluxes of such an order in such a compact device are useful in many areas such as antiterrorist materials detection, well logging, underground water monitoring, radioactive isotope production, and other applications.

[0125] Operation of such a DT-fueled plasma can also yield high intensity soft x-rays having energies in a range of approximately 1-5 keV. Such x-rays from such compact device are useful in areas such as photolithography. In one embodiment, the soft x-rays are produced from the plasma even if fusion does not occur.

[0126] From Tables 1-3, one can see that the example operating parameters of 10^{20} m^{-3} average number density at temperature of 5 keV yields a power output of approximately 57 mW. Power output can be increased dramatically by varying different plasma parameters. As previously described, the example plasma solution in reference to **Figures 6-10** are thought to generally hold when the average number density changes by a factor of approximately 10 and when the temperature changes by a factor of approximately 30.

[0127] As a relatively conservative estimate for a possible power increase, a change in temperature by a factor of approximately 20 yields a plasma temperature of approximately 100 keV, where power output is approximately 3.72 W when $n=10^{20}$ m^{-3}.

Additionally, as described above in connection with **Figures 15A-C**, electrostatic field facilitated stable plasmas can be formed with an increased volume. Thus, scaling both major and minor radii of the high aspect ratio toroid by a factor of 10 increases the volume by a factor of 10^3. Thus, because the power output is proportional to the volume of the plasma, the foregoing example 3.72 W output device can be scaled so as to produce several kilo-Watts of power. Such a device has a major radius of approximately 40 cm, which is still a relatively compact device for a power generator.

[0128] Various example plasma devices described herein can be operated by including an example start-up process that facilitates formation of a stable and confined plasma. The example start-up process is described in context of a plasma device having a toroidal geometry where both toroidal (axial) and poloidal (azimuthal) magnetic fields play a substantial role in confinement. Similar start-up process generally applies to the Z, theta and screw pinch concepts described herein.

[0129] In one embodiment, a vacuum toroidal magnetic field is established by current-carrying toroidal field coils wound in the poloidal direction (such as that shown in **Figures 17A and B**). Next, neutral gas is puffed into the vacuum chamber and a forced breakdown ionizes the gas yielding a relatively cold and substantially neutral plasma. In a time short compared to the recombination time of electrons and ions, the current in the primary winding of a transformer (such as that shown in **Figures 16A and B**) is ramped up. A change in magnetic flux through the central portion of the torus induces a toroidal (axial) current which produces a poloidal (azimuthal) magnetic field. This current can cause resistive Joule heating of the plasma to approximately 2 - 3 keV.

[0130] Thus, the foregoing example start-up process can bring the plasma into a parameter regime of substantial densities and temperatures that characterize the plasma environment. Subsequently, the plasma proceeds toward a stable, confined equilibrium configuration via relaxation processes with the concomitant development of a substantial, radial electrostatic field that provides confinement for the ions. Additional heating mechanisms such as radio frequency heating can be used to further increase the plasma temperature and hence the probability of fusion events occurring. in the plasma environment.

[0131] Although the above-disclosed embodiments have shown, described, and pointed out the fundamental novel features of the invention as applied to the above-disclosed

embodiments, it should be understood that various omissions, substitutions, and changes in the form of the detail of the devices, systems, and/or methods shown may be made by those skilled in the art without departing from the scope of the invention. Consequently, the scope of the invention should not be limited to the foregoing description, but should be defined by the appended claims.